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RADIO-FREQUENCY IGNITION HAZARDS: the choice of reference aerial for available-power calculations

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RADIO-FREQUENCY IGNITION HAZARDS : THE CHOICE OF REFERENCE AERIAL FOR AVAILABLE-POWER CALCULATIONS

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Summary

Structures in petrochemical plants can act as receiving aerials and extract power from radio waves; if a spark is generated there is a risk that flammable vapours might be ignited. The power available from a structure is closely related to that available from a small loss-free reference aerial in the same location, the ratio of the two powers being known as the efficiency. The powers available from various types of aerials and structures are considered, taking account of the effect of the ground. It is concluded that the most convenient reference is a small aerial in free space, with the efficiency of the structure defined so as to include, among other things, the effect of proximity to the ground.

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RADIO-FREQUENCY IGNITION HAZARDS : THE CHOICE OF REFERENCE AERIAL FOR AVAILABLE-POWER CALCULATIONS

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1. Introduction

Structures in petrochemical plants can act as receiving aerials and extract power from radio waves. If sufficient power is available, a spark formed at an intermittent contact in a structure could ignite a flammable vapour and cause a hazard. A knowledge of the maximum power which can be extracted from the structure is therefore an essential requirement. The maximum available power is closely related to that available from a small loss-free reference aerial in the same location, the ratio of the two powers being known as the efficiency.

This report is concerned with the choice of reference aerial and with the power which can be extracted from it. In the original British Standard on radio-frequency ignition hazards[1] the reference aerial was assumed to be a small loop or dipole in free space. It is known, however, that the power available from such an aerial is halved when it is situated very close to perfectly-conducting ground. Since structures which act as inadvertant receiving aerials are never far from the ground, the validity of using an aerial in free space as the reference has been questioned. This report considers the problem in some detail.

The power which can be extracted from a pair of terminals connected to a structure, or indeed from any aerial, is greatest when the terminating impedance is the complex conjugate of the aerial impedance. The maximum power P is then

$$P = \frac{V^2}{4R} \tag{1}$$

where V is the open-circuit voltage at the terminals, and R is the resistive part of the aerial impedance. The sections which follow are concerned with the maximum power available from various types of aerials and structures, taking into account the effect of the ground.

2. The power available from small aerials

This section considers how the power available from a small aerial, which might be used as a reference, varies with height above ground. A small aerial is one whose dimensions are small compared with the free-space wavelength.

There are two basic types of small aerial; the electric dipole and the loop. These two aerials are complementary in the sense that they have identical radiation patterns in free space, but with electric and magnetic field vectors interchanged.

The small aerials considered in this section are assumed to have no resistive loss. The resistive part of the input impedance (R in Equation (1)) is then equal to the radiation resistance. The ground is also assumed in this section to be perfectly conducting.

2.1. Small aerial in free space

It is shown in Appendix 1 that the maximum power which can be extracted from a small aerial in free space, illuminated by a plane wave whose power flux density* is S, is given by

$$P = \frac{3S\lambda^2}{8\pi} \approx \frac{S\lambda^2}{8.4} \tag{2}$$

where λ is the free-space wavelength. Equation (2) applies equally to loops and electric dipoles, provided their size is small compared with λ and they have no resistive losses.

2.2. Small aerial on the ground

Suppose now that the aerial is situated on perfectly-conducting ground and oriented in such a way that it would radiate a vertically-polarised wave. This requirement is satisfied by a loop if its axis is horizontal or by a dipole if its axis is vertical.

Consider the aerial used as a radiating element by injecting power. If the current in the aerial is unchanged, the ground plane

(a) doubles the field strength in the upper hemisphere; the power radiated in that hemisphere is therefore quadrupled,

and (b) prevents power from being radiated in the lower hemisphere.

The total power radiated is therefore doubled and, since the aerial current is unchanged, the radiation resistance is also doubled.

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* The use of power flux density S, measured (in SI units) in watts per square metre, is useful in these calculations. For a plane wavefront in free space, a power flux density of 1 W/m^2 corresponds to a field strength of about 20 V/m or 146 dB(μV/m).

Consider now the same element used as an effective receiving aerial. If the power flux density of the wave in which the aerial is immersed is unchanged, the open-circuit voltage V of Equation (1) will be unchanged but, since R has been doubled, P will be halved. It follows therefore that the maximum power which can be extracted from a small loss-free loop or dipole close to perfectly-conducting ground is given by

$$P \approx \frac{S\lambda^2}{16.8} \qquad (3)$$

where S is the power flux density of the wave in which the aerial is immersed. This result also applies to short vertical monopoles, to folded monopoles and to small rectangular loops in which the ground plane forms one side.

It is well known that the gain of a simple aerial close to the ground is 3 dB greater than that of a similar aerial in free space, because the radiated power is confined to the upper hemisphere and the total power which must be radiated in order to establish a given field strength is halved. There is a paradox because it has just been shown that the presence of the ground apparently halves the power which can be extracted from a wave incident on the aerial, even though its gain has been doubled.

There is, however, no discrepancy if the combination of aerial and ground plane is regarded as a complete aerial system. If the aerial transmits, its gain is 3 dB greater than that of a similar aerial in free space, for the reasons just stated. If it receives we must consider reception by the system as a whole rather than reception by the aerial alone. If a downcoming sky wave is incident upon the system, ground reflection will double the strength of the field component (electric or magnetic) to which the aerial responds and the open-circuit voltage V of Equation (1) will be doubled. Since the radiation resistance has also been doubled it follows that the value of P given by Equation (1) will be twice the value which can be extracted from a similar aerial in free-space; this is consistent with a gain of 3 dB.

If the sky wave is incident at a very low angle, ground reflection will increase the power flux density of the wave passing the aerial by a factor of 4. Although the power extracted from the wave will be doubled, the power extracted for a given power flux density will in fact be halved, which is the situation described by Equation (3). Because a ground wave is indistinguishable, at the receiving point, from a very low angle sky wave, it follows that Equation (3) also applies to a ground wave whose total power flux density is equal to S.

The conclusion, therefore, is that Equation (3) applies to aerials close to the ground, provided S represents the power flux density of the wave actually passing the aerial and not the power flux density of the wave incident upon the ground plane from a distant source. In the special case of a ground wave, S is the power flux density of the ground wave at the position occupied by the aerial.

2.3. Small aerial near the ground

It has been shown that the power which can be extracted from a small aerial is halved if it is situated on perfectly-conducting ground. This section considers how the available power varies as the aerial approaches the ground.

Equation (1) shows that P depends on radiation resistance and it follows that a more general expression for the power which can be extracted from a small aerial is

$$P \approx \frac{S\lambda^2 R_0}{8.4R} \qquad (4)$$

where R_0 *is the free-space radiation resistance* and R is the radiation resistance of the aerial in the presence of the ground. Equation (4) is quite general and applies to any aerial orientation or height above ground. For the particular orientations described in Section 2.2.,

$$R = R_0 + R_m \qquad (5)$$

where R_m is the mutual resistance between the aerial and its image. The value of R_m tends to R_0 as the aerial approaches the ground and Equation (4) then gives the result stated in Equation (3).

Equation (4) shows that the presence of the ground modifies the free-space value of P by the factor R_0/R. From Equation (5), the reciprocal of this factor is

$$\frac{R}{R_0} = 1 + \frac{R_m}{R_0} \qquad (6)$$

In Appendix 2 it is shown that, for small loops with horizontal axes

$$\frac{R_m}{R_0} = \frac{3}{2\theta}\left[\sin\theta + \frac{\cos\theta}{\theta} - \frac{\sin\theta}{\theta^2}\right] \qquad (7)$$

where $\theta = 4\pi h/\lambda$ and h is the height of the loop above ground. The corresponding expression for small vertical electric dipoles, also derived in Appendix 2, is

$$\frac{R_m}{R_o} = \frac{3}{\theta^2}\left[-\cos\theta + \frac{\sin\theta}{\theta}\right] \qquad (8)$$

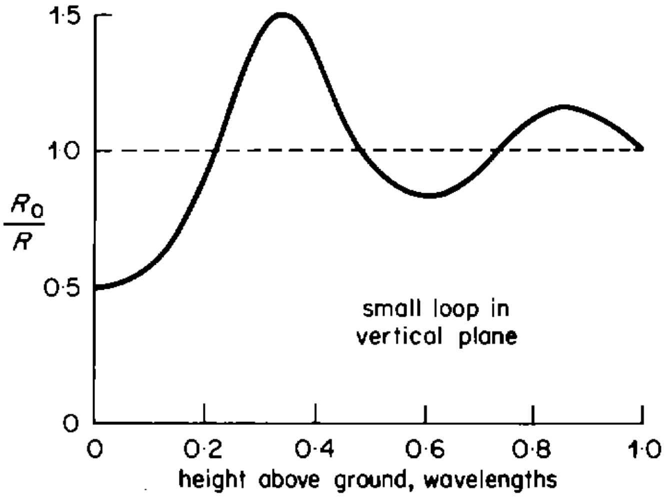

Fig. 1 - Variation of available power with height above ground.

The power available is the free-space value multiplied by R_0/R.

Fig. 1 shows how the factor R_0/R varies with height above ground, for both kinds of aerial. When h=0, R_0/R=0.5 and P is given by Equation (3). As h increases, R_0/R tends asymptotically to 1.0, when P is given by Equation (2). It is worth noting that R_0/R exceeds 1.0 for some values of h; the power which aerials at these heights could extract from a wave of given power flux density would therefore exceed the power extracted if they were in free space.

3. Aerials comparable in size with the wavelength

If the size of an aerial is comparable with the wavelength, the power which it can extract from an incident wave may exceed that which can be extracted by a small aerial, provided it is suitably oriented. In free space, the power which can be extracted by such an aerial is equal to that given by Equation (2), multiplied by the power gain which applies to the direction of arrival of the incident radiation. The gain is expressed relative to that of a small electric dipole or of a small loop.

If the aerial is close to the ground and its height is small compared with the wavelength, the available power will be further multiplied by one of the factors shown in Fig. 1. But if the height of the aerial is comparable with the wavelength, Fig.1 will no longer apply. Since a tall aerial can be regarded as an array of small aerials, the effective value of R_0/R can be derived from the weighted average of R_0/R over the height of the aerial. Averaging of the rapid variation of R_0/R with height shown in Fig. 1 suggests that the value of R_0/R for tall aerials may be closer to 1.0 than is the case with small aerials. It can be shown, for example, that the power available from a vertical $\lambda/2$ dipole is reduced by only 27% when it is placed as close to the ground as possible, instead of being halved. Thus the ground has much less effect on the power available from tall aerials then it has on small aerials.

4. The effect of imperfectly-conducting ground

Sections 2 and 3 have considered the effect of perfectly-conducting ground on the power available from various types of aerial. This power will be reduced if the ground is an imperfect conductor, because ground loss increases the resistive part of the aerial impedance. If the aerial were to transmit, losses associated with currents flowing in the ground would reduce its efficiency; by reciprocity the efficiency of the aerial when receiving would be reduced by the same amount.

5. The power available from practical aerials

In a draft revision of Reference 1, it was proposed that the power available from a practical aerial of known efficiency should be calculated from that which can be extracted from a small aerial in free space, even though the practical aerial might in fact be situated on the ground. In an alternative procedure for small ground-based aerials, which has rather more theoretical justification, the efficiency is multiplied by the power which can be extracted from a small aerial close to perfectly-conducting ground. This procedure, however, has less justification if the practical aerial is at a moderate height above ground or if its vertical dimension is comparable with the wavelength.

To overcome this difficulty it is proposed here that the reference power should always be that available from a small loss-free aerial in free space, i.e. $S\lambda^2/8.4$. The "efficiency" of any aerial would then be defined as the ratio of the available power to the reference power. Defined in this way, the "efficiency" would combine in one figure the effects of resistive losses, the proximity of the ground regardless of its conductivity, ground loss and directivity gain. Since the effects of ground loss and resistive loss are difficult to estimate for practical structures, it is proposed that "efficiency" values should be derived from measurements made on real structures, possibly expressed in the form of curves showing upper limits.

Although "efficiency" defined in this way could exceed 100% with loss-free aerials at certain heights above ground, "efficiencies" greater than 100% are unlikely to occur with real structures situated on imperfectly-conducting ground.

6. Aerials in non-uniform fields

It has been assumed up to now that the aerial is illuminated by a plane wave but reflecting objects may distort the field in real situations, giving rise to standing waves. The ratio of the electric and magnetic field strengths will no longer be 377 ohms and the concept of power flux density will be invalid. It now becomes necessary to enquire whether the aerial responds mainly to electric or magnetic fields.

If the aerial responds mainly to the electric field, S should be replaced by $E^2/377$, where E is the electric field strength in V/m. If it responds to the magnetic field, S should be replaced by $377\ H^2$, where H is the magnetic field strength in A/m. It is worth noting that most field-strength meters measure the magnetic field strength but give the result in terms of an equivalent electric field strength, assuming free-space conditions. A rod or dipole aerial must be used to measure electric field strength.

Structures which respond to electric field strength include vertical columns insulated from the ground, and earthed columns with vertical pipes acting as folded monopoles. Balanced loops respond to the magnetic field; a loop formed by a pipe bridging the gap between two columns, with terminals at the top of one of the columns, behaves as a balanced loop. A loop with terminals near the ground responds to both field components, as does a crane. In the case of a crane, the predominent field component may be determined by turning the crane round; if the induced voltage is almost independent of azimuth, then it is the electric field which predominates.

7. Conclusions

Although the power which can be extracted from a small aerial on, or very close to, perfectly-conducting ground is half the free space value, it does not differ greatly from the free space value when the aerial is only a few wavelengths above ground. The ground has even less effect on the available power if the vertical dimension of the aerial is comparable with the wavelength.

The power which can be extracted from a real structure is equal to the power which could have been extracted from the structure in the absence of losses, multiplied by its efficiency. Since proximity to the ground influences the power available from a loss-free aerial over only a limited range of aerial heights, it is proposed here that the power available from a small loss-free aerial in free space ($S\lambda^2/8.4$) should always be used as the starting point, and the "efficiency" re-defined so as to include, among other things, the effect of proximity to the ground. Efficiency values for use in hazard calculations would be derived from measurements made on typical structures.

In non-uniform fields the power flux density S should be replaced by $E^2/377$ if the structure responds mainly to the electric field E, or by $377H^2$ if it responds mainly to the magnetic field H.

8. References

1. Guide to protection against ignition and detonation initiated by radio frequency radiation. British Standard BS 4992, 1974.

2. SCHELKUNOFF, S.A. Electromagnetic Waves, van Nostrand, 1943, Chapter 6.

3. JORDAN, E.C. *and* BALMAIN, K.G. Electromagnetic Waves and Radiating Systems, Prentice Hall, 1968.

9. Appendix 1

THE MAXIMUM POWER WHICH CAN BE EXTRACTED FROM A SMALL AERIAL

In the absence of losses, the maximum power which can be extracted from any aerial is

$$P = \frac{V^2}{4R_0} \tag{9}$$

where V is the open-circuit voltage at its terminals and R_0 is its radiation resistance. P is calculated below for a small loop and for a short electric dipole, both in free space.

9.1. Small loop

The open-circuit voltage V is

$$V = \omega\mu_0 HA \tag{10}$$

where ω = $2\pi f$
f = frequency
μ_0 = magnetic permeability of free space = $4\pi \times 10^{-7}$ Henrys/m
H = magnetic field strength
A = area of loop

According to Equation (10—3) of Reference 2, the free-space radiation resistance of the loop is given by

$$R_0 = 320\pi^4 \frac{A^2}{\lambda^4} \tag{11}$$

where λ is the wavelength. From Equations (9), (10) and (11) it may then be shown that

$$P = 45\,(H\lambda)^2 \tag{12}$$

Since $H^2 = S/120\pi$, where S is the power flux density of the incident wave, Equation (12) may be written as

$$P = \frac{3S\lambda^2}{8\pi} \tag{13}$$

9.2. Short electric dipole

It is assumed here that the electric dipole, of total length L, would have a triangular current distribution if driven at its mid point; this kind of dipole can be realised in practice, unlike the hypothetical doublet with a uniform current distribution which is often assumed.

The open-circuit voltage is

$$V = EL/2 \tag{14}$$

where E is the electric field strength. The free-space radiation resistance, given by Equation (10.54a) of Reference 3, is

$$R_0 = 20\pi^2 \left[\frac{L}{\lambda}\right]^2 \tag{15}$$

From Equations (9), (14) and (15), it follows that

$$P = \frac{(E\lambda)^2}{320\pi^2} \tag{16}$$

If the substitution $E^2 = 120\pi S$ is made in Equation (16), the result given by Equation (13) is obtained.

10. Appendix 2

MUTUAL RESISTANCE BETWEEN SMALL LOOPS AND DIPOLES

The mutual impedance Z_m between an aerial and its image in the ground is given by

$$Z_m = \frac{V_i}{I} \tag{17}$$

where V_i is the voltage which would be induced in the aerial by an identical aerial, carrying a current I, located in the position occupied by the image. Z_m is derived below for small loops and short electric dipoles and is expressed in terms of free-space radiation resistance R_o.

10.1. Small loop

The plane of the loop is assumed to be vertical. From Equation (17-5) of Reference 2 it may be shown that the magnetic field H_i which couples with the loop as a result of the image current I is given by

$$H_i = \frac{2\pi^2 AI}{\lambda^3 \theta} \left[1 + \frac{1}{j\theta} - \frac{1}{\theta^2} \right] e^{-j\theta} \tag{18}$$

where $\theta = 4\pi h/\lambda$ and h is the height of the centre of the loop above ground. The voltage V_i induced in the loop by the image current is

$$V_i = j\omega\mu_o H_i A \tag{19}$$

From Equations (17), (18) and (19) it follows that

$$Z_m = \frac{j\,2\pi^2 \omega\mu_o A^2}{\lambda^3 \theta} \left[1 + \frac{1}{j\theta} - \frac{1}{\theta^2} \right] e^{-j\theta} \tag{20}$$

It then follows from Equations (11) and (20) that

$$\begin{aligned} \frac{Z_m}{R_o} &= \frac{j3}{2\theta} \left[1 + \frac{1}{j\theta} - \frac{1}{\theta^2} \right] e^{-j\theta} \\ &= \frac{3}{2\theta} \left\{ \sin\theta + \frac{\cos\theta}{\theta} - \frac{\sin\theta}{\theta^2} + j \left[\cos\theta - \frac{\sin\theta}{\theta} - \frac{\cos\theta}{\theta^2} \right] \right\} \end{aligned} \tag{21}$$

The real part of Equation (21) is equal to R_m/R_o

10.2. Short electric dipole

The dipole, of length L, has terminals at its mid point. The image current is assued to have a triangular distribution, with a maximum value of I at the terminals. The axis of the dipole is vertical.

From Equation (2-11) of Reference 2 it may be shown that the electric field which couples with the dipole as a result of the image current is

$$E_i = -\frac{120\,\pi^2 IL}{(\lambda\theta)^2} \left[1 + \frac{1}{j\theta} \right] e^{-j\theta} \tag{22}$$

The induced voltage V_i is equal to $E_i L/2$. It therefore follows that

$$Z_m = -\ 60 \left(\frac{\pi L}{\lambda\theta}\right)^2 \left[1 + \frac{1}{j\theta}\right] e^{-j\theta} \tag{23}$$

Since R_o is given by Equation (15), it then follows that

$$\begin{aligned} \frac{Z_m}{R_o} &= \frac{-3}{\theta^2} \left[1 + \frac{1}{j\theta}\right] e^{-j\theta} \\ &= \frac{-3}{\theta^2} \left\{ -\cos\theta + \frac{\sin\theta}{\theta} + j \left[\sin\theta + \frac{\cos\theta}{\theta} \right] \right\} \end{aligned} \tag{24}$$

R_m/R_o is equal to the real part of Equation (24).

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